Conservation agriculture in African mixed crop-livestock systems: Expanding the niche

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ABSTRACT

Competition for crop residues between livestock feeding and soil mulching is a major cause of the low and slow adoption of conservation agriculture (CA) in sub-Saharan Africa. Retaining crop residues in the field is not only a prerequisite for CA but may also be the most viable option for African farmers to retain their fields in a productive state. In this paper, (1) we explore the possibility of increasing the quantity of crop residue available by closing the maize yield gap, (2) we propose interventions that can reduce crop residue demand for livestock feed, and (3) we quantify the optimum amount of crop residues required as mulch, using empirical, secondary and modeling data from Western Kenya and the Ethiopian Rift Valley. Residue retention can also be increased by reducing livestock demand. Closing the maize yield gap—i.e. achieve 90% of the water-limited yield potential—and intensifying dairy production—which would promote the use of rations that are more energy-dense than cereal residue-based rations—would increase the estimated proportion of farmers retaining at least 1 t ha⁻¹ of crop residues from the current 36% to 97% in Western Kenya. In the Ethiopian Rift Valley, closing the maize yield gap and substituting mechanization to animal draught power would increase the estimated proportion of farmers retaining at least 1 t ha⁻¹ of crop residues from the current 3% to 83%. We conclude that the question is not ‘if’, but ‘how’ cereal residues can fulfill the demand of both the soil and the livestock.

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1. Introduction

Retaining crop residues as surface mulch, together with minimum soil disturbance and crop rotation and association, forms the basis of conservation agriculture (CA, Kassam et al., 2009). The environmental benefits of CA in terms of soil and water conservation are well documented (e.g., Lal, 1998; Scopel et al., 2004). CA may also generate a number of short-term benefits for farmers (Knowler and Bradshaw, 2007; Rusinamhodzi et al., 2011). Reduction in machinery and fuel costs has been one of the major incentives for the large-scale adoption of CA in North America, South America and Australia (Kassam et al., 2009). In the less mechanized systems in developing countries, CA may enable early planting, as the number of operations required to prepare the land are reduced (Hagblade and Tembo, 2003). Moreover, reduced soil water loss from runoff and evaporation (Rockström et al., 2009; Thierfelder and Wall, 2009) may result in more efficient use of rainfall by the crop and yield stabilization, particularly in dry areas (Friedrich, 2008; Erenstein, 2002, 2003).

Feeding crop residues to livestock is an alternative use particularly common in the developing world, where 75% of the milk and 60% of the meat are produced in mixed crop-livestock systems (Herrero et al., 2010; Valbuena et al., 2012). The crop residue demand by the livestock sector is unlikely to decrease in this part of the world, as meat and milk consumptions are projected to more than double by 2050 from their values in 2010 (Thornton, 2010). A trade-off arises when a particular stakeholder faces more than one objective towards a resource that cannot simultaneously be achieved (Grimble and Wellard, 1997). Due to the multiple benefits livestock generates (Schiere et al., 2002; Powell et al., 2004; Rufino et al., 2006; Herrero et al., 2010; McDermott et al., 2010), mixed crop-livestock African farmers generally feed the bulk of their crop residues to livestock and sacrifice on soil mulching i.e. they trade soil mulching for livestock feeding (Valbuena et al., 2012). When insufficient quantities of crop residues are retained as surface mulch, minimum tillage alone may lead to lower yields compared with the current farm practices, particularly on soils that are prone to crusting and compaction (Baudron et al., 2012). Based on those observations, some authors have concluded that CA would only fit in a limited set of socio-ecological niches in Africa, which is dominated by mixed crop-livestock systems (Giller et al., 2009, 2011; Andersson and Giller, 2012).
Table 1

<table>
<thead>
<tr>
<th>Sub-objectives</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantifying current crop residue use</td>
<td>Calculations from farm survey data</td>
</tr>
<tr>
<td>Exploring alternatives to increase cereal grain and residue yield</td>
<td>Yield gap analysis from farm survey data</td>
</tr>
<tr>
<td>Exploring alternatives to reduce livestock demand for crop residues By stimulating livestock productivity</td>
<td>Feeding trial to establish the relationship between cereal residue feeding and livestock productivity</td>
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<td>By providing substitute to the main functions livestock plays</td>
<td>Calculations from farm survey data to quantify livestock functions</td>
</tr>
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<td>On-station trial to establish the relationship between mulching rate and grain yield</td>
</tr>
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</table>

Several studies have quantified and explained crop residue trade-offs in mixed crop-livestock systems (e.g. Erenstein, 2002, 2003; Valbuena et al., 2012) but few have explored alternatives to feed both the livestock and the soil, and thus expand the niche in which CA would fit. Retaining part of the crop residues in African fields is not only a prerequisite to CA adoption: it may also be the most viable option to maintain them in a productive state, whether they are ploughed in or retained as surface mulch. It is widely acknowledged that increasing the use of mineral fertilizer, currently estimated at an average 8 kg ha⁻¹ (Groot, 2009), is necessary to improve crop productivity in Africa (e.g. Vitousek et al., 2009). Soils with a low soil organic carbon content, however, generally respond poorly or not at all to mineral fertilizers (Lal, 2010; Vanlauwe et al., 2010). An adequate annual input of organic material is crucial to maintain soil organic carbon, especially in coarse-textured soils (Chivunge et al., 2006; Stewart et al., 2007; Luo et al., 2010). The quantity of manure and plant biomass (other than crop residues) available to African farmers as organic input is generally low (Vanlauwe and Giller, 2006; Tittonell and Giller, 2012). Manure and plant biomass, when available, are also bulky materials: their collection, transport and application are labour-intensive, and they are only applied to a minority of fields (Tittonell et al., 2005). On the other hand, crop residues represent the most abundant organic material available to farmers (Lal, 2005) and their retention in situ does not require any labour. Thus, retaining part of the crop residues produced in African fields is a priority to sustain agricultural intensification in the continent. In circumstances where the retention of these residues as surface mulch leads to short-term benefits for farmers, it may also expand the adoption of CA.

The objective of this study was to quantify crop residue trade-offs and explore alternatives to overcome them in two study sites known for their high livestock densities: Western Kenya and the Ethiopian Rift Valley. Both sites are part of the maize mixed farming system as defined by FAO (http://www.fao.org/DOCREP/003/Y1860E). Western Kenya corresponds to the wetter part of this domain, and the Ethiopian Rift Valley to the drier part.

2. Materials and methods

2.1. General approach

A range of methods were used in this study, to fulfill four inter-related sub-objectives (Table 1). First, current crop residue uses were quantified, using farm survey data. Second, alternatives were explored to increase the quantity of crop residues retained in the field by (1) increasing the quantity produced and (2) reducing livestock demand. These explorations were made using farm survey data and feed trial data. Third, the impact of crop residue mulching on crop productivity was established using on-station trial data.

2.2. Study areas

2.2.1. Western Kenya

In Western Kenya, the study was conducted in the District of Bungoma, located between 34°22 and 34°03 East and 0°25 and 1°08 North, and the District of Siaya, located between 33°57 and 34°33 East and 0°18 and 0°26 North. Bungoma lies between 1,300 and 3,100 m above sea level, whilst Siaya lies between 1,100 and 1,500 m above sea level. Bungoma receives bimodal rainfall ranging from 1,200 mm to 1,800 mm per year, with the long rains falling between March and July and the short rains between August and November. Higher regions of Siaya receive 1,800 mm to 2,000 mm of rainfall per annum, while the lower regions receive 800 mm to 1,600 mm per annum. Average temperatures in Bungoma range from 16°C to 30°C with an average of 23°C. In the two districts, maize (Zea mays L.), common bean (Phaseolus vulgaris L.), cassava (Manihot esculenta Crantz), sorghum (Sorghum bicolor (L.) Moench), pearl millet (Pennisetum glaucum (L.) R. Br.), sweet potatoes (Ipomoea batatas (L.) Lam.), and bananas (Musa sp. L.) are the main food crops grown, whilst sugarcane (Saccharum sp. L.), tea (Camellia sinensis (L.) Kuntze), cotton (Gossypium hirsutum L.) and tobacco (Nicotina sp. L.) are the main cash crops. The major livestock enterprises are dairy cattle and poultry. This study area is referred to as ‘Western Kenya’ in the rest of the paper.

On-station research trials in Western Kenya were conducted at Kakamega Agricultural Research Center. The station is located at 34°45 East, and 0°16 North, at an altitude of 1,585 m above sea level, receives between 1,890 and 1,920 mm of annual rainfall, and is characterized by a mean minimum temperature of 14°C, and a mean maximum temperature of 27°C. Soils are dominated by mollic Nitosols.

2.2.2. Ethiopian Rift Valley

In Ethiopia, the study was conducted in four districts of the Ethiopian Rift Valley: Adama, Adami Tulu, Boset, and Dodota Sire, located between 38°40 and 39°30 East and 7°50 and 8°40 North. The area lies between 1,500 and 1,950 m above sea level, and is characterized by low and erratic rainfalls comprised between 500 and 800 mm and high evapo-transpiration rates. Mean minimum temperatures range from 7.8 to 14.4°C and mean maximum temperatures from 27.2 to 28.6°C. The study area is characterized by two clearly defined seasons: a main rainy season from June to October, and a long dry season from November to May. Tef (Eragrostis tef (Zucc.) Trotter), maize, wheat (Triticum sp. L.) and common bean are the main crops grown. Cattle, goats, horses and donkeys are the main livestock types farmers keep. This study area is referred to as the ‘Ethiopian Rift Valley’ in the rest of the paper.

On-station research trials in the Ethiopian Rift Valley were conducted at Melkassa Agricultural Research Center. The station is located at 39°12′ East, and 8°24′ North, at an altitude of 1,550 m above sea level, receives 763 mm of average rainfall annually, and is characterized by a mean minimum temperature of 28.6°C, and a mean maximum temperature of 13.8°C. Soil is dominantly loamy and clay loamy.

2.3. Farm survey

A sample of farms was randomly selected in the two study areas: 299 in Western Kenya and 344 farms in the Ethiopian Rift Valley. The head of each farm was interviewed using a standardized questionnaire addressing size and composition of the household,
production capital (e.g. land, equipment), crop and livestock production and management, and income generating activities.

2.4. Effect of soil mulching on maize productivity

On-station trials were conducted in 2011 and 2012 to test the effect of soil mulching on maize productivity in Kakamega Agricultural Research Center and Melkassa Agricultural Research Center. In both sites, each plot was 100 m², and maize was seeded in rows spaced 75 cm apart, with a plant-to-plant spacing within a row of 25 cm. Maize grain yield was estimated by harvesting maize ears at maturity, shelling, and determining grain moisture content by oven-drying a grain subsample for 48 h at 60–70 °C to determine its moisture content. Similarly, stover yield was estimated by counting the number of plants in the harvested area, sampling 15 representative ones, weighing them and determining the moisture content of a subsample oven-dried for 48 h at 60–70 °C.

In Kakamega Agricultural Research Center, four blocks were seeded to the maize variety KSTP 94, during the long rains of 2011. Mineral fertilizer was applied at a rate of 125 kg ha⁻¹ of diammonium phosphate at planting and 125 kg ha⁻¹ of calcium ammonium nitrate was side-dressed at the six-leaf growth stage. After harvest, each block was divided into five treatments with 0, 25, 50, 75 and 100% of crop residues retained as surface mulch. During the following seasons—i.e. short rains of 2011 and long rains of 2012—maize was seeded through the mulch by opening shallow planting stations, without prior land preparation. For each plot, the same level of residue retention was used during the different seasons.

In the trials conducted at Melkassa Agricultural Research Center, three blocks were seeded to the maize variety Melkassa 2 during the 2011 season. Mineral fertilizer was applied at a rate of 100 kg ha⁻¹ of diammonium phosphate and 25 kg ha⁻¹ of urea at planting and 25 kg ha⁻¹ of urea was side-dressed at the six-leaf growth stage. After harvest, each block was divided in four treatments with 0, 33, 67 and 100% of crop residues retained as surface mulch. During the next season (2012), maize was seeded through the mulch by opening shallow planting station, without prior land preparation.

2.5. Feeding trials on dairy cows

In 2012, seven lactating Friesian cows were selected in Kakamega research station, on the basis of similar live weight (mean of 367 ± 13 kg), lactation phase (mid-lactation) and milk yield prior to the feeding trial (mean of 9.9 ± 3.1 kg milk day⁻¹). Six experimental diets containing varying levels of maize residues (maize stover, and residues from shelled maize), napier grass, and concentrates (soya bean meal, and molasses) were formulated based on their total neutral detergent fiber (NDF), total metabolizable energy (ME) and total crude protein content (CP). Each diet aimed at providing enough energy to support a milk yield of 20 L day⁻¹, for a cow in mid-lactation (i.e. requiring a CP in the ingested ration between 140 and 160 g kg⁻¹ DM). The nutritive values of the different ingredients are shown in Table 2, and the composition of each diet in Table 3.

### Table 2

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>DM (%)</th>
<th>Metabolisable energy (Mcal kg⁻¹ DM)</th>
<th>Digestibility (%)</th>
<th>Crude protein (g kg⁻¹)</th>
<th>Price (KSH kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize stover</td>
<td>97</td>
<td>1.6</td>
<td>43</td>
<td>24</td>
<td>10</td>
</tr>
<tr>
<td>Residue from shelled maize</td>
<td>87</td>
<td>3.3</td>
<td>94</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>Napier</td>
<td>30</td>
<td>2.2</td>
<td>65</td>
<td>72</td>
<td>10</td>
</tr>
<tr>
<td>Soya bean meal</td>
<td>88</td>
<td>2.2</td>
<td>89</td>
<td>500</td>
<td>15</td>
</tr>
<tr>
<td>Molasses</td>
<td>74</td>
<td>2.6</td>
<td>83</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

DM: dry matter, KSH: Kenyan Shilling.

### Table 3

Prior to being mixed in rations, the napier grass (variety Kakamega 3) and the maize stover were chopped, the residue from shelled maize was broken using a hammer mill without a sieve, the soya bean meal was milled to pass through 2 mm sieve, and the molasses was diluted with water at a 1:2 ratio. Ingredients were then weighed precisely and mixed thoroughly in a drum mixer. The feeding trial was of switch-over type, each cow receiving each ration for a period of 25 days (i.e. 10 days for ration adjustment and then 15 days for data collection) with a 3 day cross-over period. The feed was offered twice a day in the morning and afternoon. The amounts of feed offered and refused were recorded daily. Milk yield was recorded at each milking.

### Table 3

Composition of the six diet used for the feeding trial.

<table>
<thead>
<tr>
<th>Diet</th>
<th>Diet 1</th>
<th>Diet 2</th>
<th>Diet 3</th>
<th>Diet 4</th>
<th>Diet 5</th>
<th>Diet 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize stover</td>
<td>10</td>
<td>45</td>
<td>65</td>
<td>13</td>
<td>26</td>
<td>42</td>
</tr>
<tr>
<td>Residue from shelled maize</td>
<td>64</td>
<td>30</td>
<td>6</td>
<td>44</td>
<td>21</td>
<td>5</td>
</tr>
<tr>
<td>Napier</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>9</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>Soya bean meal</td>
<td>14</td>
<td>23</td>
<td>29</td>
<td>16</td>
<td>17</td>
<td>22</td>
</tr>
<tr>
<td>Molasses</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>18</td>
<td>21</td>
<td>18</td>
</tr>
</tbody>
</table>
third quartile). Then, logistic regression models were fitted through the upper boundary points on a scatter plot, i.e. the maximum maize yield response for each level of the independent variable. This analysis was done with Genstat 6.1 (2002). For each maize plot of each farm surveyed, attainable yield was calculated as the minimum of the N-limited attainable yield (obtained from the logistic regression model for N) and the P-limited attainable yield (obtained from the logistic regression model for P). Actual yields were then expressed as a fraction of the attainable yield.

2.7. Scenarios

A number of scenarios were used to predict the consequences of changes in residue production and/or residue feeding on the quantity of residues retained in the field. For scenarios of changes in residue production, the quantities of each cereal residue used as feed, fuel and for other uses were kept to their current value, and the remainder was assumed to be retained in the field. For scenarios of changes in residue feeding, the demand for cereal residues per livestock type was estimated for each farm, by converting livestock numbers into Tropical Livestock Units (TLU), which is defined as a hypothetical animal of 250 kg live weight (Le Houérou and Hoste, 1977). Bulls and oxen were assumed to be equivalent to 1.1 TLU, cows to 0.8 TLU, heifers to 0.5 TLU and calves to 0.2 TLU (Machila et al., 2003; Wondatir, 2010). Feeding by small ruminants and equines was ignored, as these are minor livestock types compared with cattle in the two study sites.

3. Results

3.1. Farm survey data

3.1.1. Analysis of current crop residue use

In Western Kenya, the majority of maize residues produced during the long rains and during the short rains was retained in the field as soil amendment (mean values of 55 ± 38% and 61 ± 37%, respectively, Fig. 1). Livestock feeding was the second use during both seasons (mean values of 28 ± 30% during the long rains and 27 ± 30% during the short rains). A minor fraction of maize residues was used as fuel, both during the long and short rains (mean values of 7 ± 16% and 3 ± 11%, respectively). In the Ethiopian Rift Valley,.

![Pie charts](image_url)

**Fig. 1.** Mean use of maize stover in Western Kenya during the long rains and the short rains (estimated from 299 farms), and of maize stover, tef straw, wheat straw and barley straw in the Ethiopian Rift Valley (estimated from 344 farms).

![Frequency distributions](image_url)

**Fig. 2.** Frequency distribution of farms according to their current rate of residue retention in (a) Western Kenya and (b) the Ethiopian Rift Valley; frequency distribution of farms according to their projected rate of residue retention in Western Kenya assuming a scenario (c) of livestock intensification—i.e. farmers feeding their cows with rations containing no maize residue, (e) of farmers “closing the maize yield gap” — i.e. achieving 90% of the water-limited yield potential, and (h) of livestock intensification and closing the yield gap; and frequency distribution of farms according to their projected rate of residue retention in the Ethiopian Rift Valley assuming a scenario of all farmers (d) substituting mechanization to animal draught power, (f) closing the yield gap, and (h) substituting mechanization to animal draught power and at the same time closing the yield gap. From (a) to (c), (e), and (g), the proportion of farmers in Western Kenya retaining at least 1 t ha⁻¹ of residues in the field increases from 36% to 49%, 93% and 97%. From (b) to (d), (f), and (h), the proportion of farmers in the Ethiopian Rift Valley retaining at least 1 t ha⁻¹ of residues in the field increases from 3% to 25%, 60% and 83%.
the majority of maize, tef, wheat, barley, and sorghum residues was used as livestock feed (mean values of 67 ± 22%, 88 ± 23%, 85 ± 24%, 88 ± 25%, 58 ± 33%, respectively). A small fraction of maize and sorghum residues was used as fuel (22 ± 17% and 17 ± 19%, respectively), while no tef, wheat, and barley residue was used as fuel. A minor fraction of maize, tef, wheat, barley, and sorghum residues was retained in the field as soil amendment (7 ± 14%, 7 ± 20%, 9 ± 16%, 7 ± 16%, 9 ± 19%).

Currently, 19% of the farmers in Western Kenya (Fig. 2a) and 69% of the farmers in the Ethiopian Rift Valley (Fig. 2b) are not retaining any crop residue in their fields. Only 36% of the farmers in Western Kenya and 3% of the farmers in the Ethiopian Rift Valley currently retain 1 t ha−1 of crop residues or more.

3.1.2. Yield gap analysis for maize

The highest estimated yield attained in Western Kenya was 6750 kg ha−1 during the short rains of 2011 and 2700 kg ha−1 during the short rains of 2011 (Fig. 3a and b). It was 8120 kg ha−1 in the Ethiopian Rift Valley in 2011 (Fig. 3c and d). These yields can be considered the water-limited yield potentials, defined as the maximum yield achievable under rainfed conditions without irrigation if soil water capture and storage is optimal and nutrient constraints are released (Tittelong and Giller, 2012). When using N application rate and P application rate as independent variables, the boundary lines showed an increase in the attainable yield with increasing application rates of N and P in both sites, illustrating the fact that maize yield is limited by N and P in both sites. Table 4 gives the values of N and P application rates required to achieve 90% of the water-limited yield potentials in 2011 in Western Kenya (during the short and the long rains) and in the Ethiopian Rift Valley. These values were calculated using the logistic regression models fitted through the upper boundary points of maize yield as a function of N and P fertilization rates.

Table 4: Nitrogen (N) and phosphorus (P) fertilization rate required to reach 90% of the water-limited yield potential in Western Kenya during the short rains (October–November) and the long rains (March–June) and in the Ethiopian Rift Valley.

<table>
<thead>
<tr>
<th></th>
<th>N (kg ha−1)</th>
<th>P (kg ha−1)</th>
<th>90% of water-limited yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Kenya Short Rains</td>
<td>122.8</td>
<td>45.5</td>
<td>2430</td>
</tr>
<tr>
<td>Western Kenya Long Rains</td>
<td>75.7</td>
<td>30.3</td>
<td>6075</td>
</tr>
<tr>
<td>Ethiopian Rift Valley</td>
<td>25.0</td>
<td>20.3</td>
<td>7308</td>
</tr>
</tbody>
</table>

3.1.3. Analysis of livestock functions

The density of cattle in the Ethiopian Rift Valley was significantly higher than in Western Kenya (means of 5.69 ± 6.11
TLU ha\(^{-1}\) cropland and 4.04 ± 6.20 TLU ha\(^{-1}\) cropland, respectively, (Table 5). In Western Kenya, the herd was dominated by cows (mean of 62 ± 32% of the total TLU). In the Ethiopian Rift Valley, oxen were the predominant cattle type (mean of 42 ± 24% of the total TLU) followed by cows (mean of 36 ± 21% of the total TLU). Although there was no difference between the Ethiopian Rift Valley and Western Kenya in the calf/cow ratio (means of 0.60 ± 0.42 and 0.61 ± 0.59, respectively), the heifer/cow ratio was significantly higher in the Ethiopian Rift Valley compared with the ratio in Western Kenya (means of 0.42 ± 0.54 and 0.17 ± 0.48, respectively). Manure application on cropland was significantly higher in Western Kenya compared with that in the Ethiopian Rift Valley (means of 1700 ± 3882 kg ha\(^{-1}\) and 423 ± 1003 kg ha\(^{-1}\), respectively). The intensity of manure collection from cattle was also significantly higher in Western Kenya compared with the Ethiopian Rift Valley (means of 664 ± 1766 kg TLU\(^{-1}\) and 81 ± 172 kg TLU\(^{-1}\), respectively). Milk production was also significantly higher in Western Kenya compared with the Ethiopian Rift Valley (means of 421 ± 718 L cow\(^{-1}\) year\(^{-1}\) and 160 ± 171 L cow\(^{-1}\) year\(^{-1}\) respectively).

Table 5 In Western Kenya, the number of dairy cows and the quantity of manure applied on the farm had a significant influence on the cereal production of the farm (\(F = 31.78, P < 0.001\), Fig. 5a). In 2011, farmers having no dairy cows and applying less than one ton of manure in their farms produced an average of 1208 ± 1999 kg cereals, whilst farmers having no dairy cow but applying at least one ton of manure in their farms produced an average of 2064 ± 2695 kg cereals, and farmers having at least one dairy cow produced an average of 4659 ± 7979 kg cereals. In the Ethiopian Rift Valley, the number of pairs of oxen owned had a significant influence on the cereal production of the farm (\(F = 51.91, P < 0.001\)): in 2011, farmers having no oxen produced an average of 1934 ± 2227 kg cereals, whilst farmers having one pair of oxen produced an average of 3989 ± 3108 kg cereals, and farmers having at least two pairs of oxen produced an average of 6812 ± 6023 kg cereals (Fig. 5b).

3.2. Trial data

3.2.1. Effect of soil mulching on maize grain yield

During the short rains in Kakamega, the quantity of surface mulch in the different treatments was between 2.0 and 3.2 t ha\(^{-1}\) (Fig. 6a). However, the quantity of mulch retained had no effect on maize grain yield. During the long rains in Kakamega, as well as in Melkassa, maize grain yield was found to increase non-linearly with the quantity of soil mulch applied (Fig. 6b and c). During the long rains of Kakamega, a plateau was reached in maize grain yield with a surface mulch of approximately 1 t ha\(^{-1}\) of maize stover, implying that quantities of maize stover beyond this threshold did not influence maize grain yield significantly, and could thus be allocated to other uses—e.g. livestock feeding—with no yield penalty. Similarly in Melkassa, a plateau was reached with a surface mulch of 3 t ha\(^{-1}\).

Table 5 Characteristic of the average cattle herd in Western Kenya and in the Ethiopian Rift Valley.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Western Kenya</th>
<th>Ethiopian Rift Valley</th>
<th>(P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle density (TLU/ha cultivated)</td>
<td>4.04 ± 6.20</td>
<td>5.69 ± 6.11</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Herd composition (% TLU)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxen</td>
<td>0.12 ± 0.26</td>
<td>0.42 ± 0.24</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Bulls</td>
<td>0.10 ± 0.21</td>
<td>0.07 ± 0.11</td>
<td>n.s.</td>
</tr>
<tr>
<td>Cows</td>
<td>0.62 ± 0.32</td>
<td>0.36 ± 0.21</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Heifers</td>
<td>0.05 ± 0.14</td>
<td>0.10 ± 0.15</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Calves</td>
<td>0.12 ± 0.19</td>
<td>0.05 ± 0.07</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Herd management</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heifer/Cow</td>
<td>0.17 ± 0.48</td>
<td>0.42 ± 0.54</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Calf/Cow</td>
<td>0.61 ± 0.59</td>
<td>0.60 ± 0.42</td>
<td>n.s.</td>
</tr>
<tr>
<td>Manure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied (kg/ha)</td>
<td>1700 ± 3882</td>
<td>423 ± 1003</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Collected (kg/TLU)</td>
<td>664 ± 1766</td>
<td>81 ± 172</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Milk/(L/cow)</td>
<td>421 ± 718</td>
<td>160 ± 171</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Standard errors are given after the signs `±`. \(P\) values are given for Kruskal–Wallis tests comparing medians between Western Kenya and the Ethiopian Rift Valley.
This higher threshold compared to that in Kakamega may be due to the fact that rainfall in Melkassa is lower and more erratic than in Kakamega, whilst evapotranspiration is higher. It may also be due to differences in soil texture and soil organic carbon content.

### 3.2.2. Effect of maize residue feeding on dairy production

In the feeding trial conducted in Kakamega, the production cost per litre of milk decreased with decreasing amounts of maize residues in the ration of dairy cows (Fig. 7a). Moreover, the maximum cost per litre of milk production decreased with increasing milk yield (Fig. 7b). Therefore, the profitability of milk production tended to increase with decreasing amounts of maize residues in the ration and with increasing milk yields.

### 3.3. Scenarios

Assuming a scenario where all farmers in Western Kenya feed their cows with rations containing no maize residue but with rations composed of ingredients having lower fiber contents and higher energy densities, the proportion of farmers not retaining any residue in their field is predicted to decrease from 19% to 8% (Fig. 2a and c). Concomitantly, the proportion of farmers retaining at least 1 t ha\(^{-1}\) of crop residue would increase from 36% to 49%. Assuming a scenario where all the farmers in Western Kenya 'close the yield gap'—i.e. achieving 90% of the water-limited yield potential—the proportion of farmers not retaining any residue in their fields would decrease further to 3% and the proportion of farmers retaining at least 1 t ha\(^{-1}\) of crop residue would increase further to 93% (Fig. 2e). Finally, assuming a scenario where all farmers in Western Kenya both feed their cows with rations containing no maize residues and close the yield gap, the proportion of farmers not retaining any residue in their fields would be 1% only, and the proportion of farmers retaining at least 1 t ha\(^{-1}\) of crop residues would be as high as 97% (Fig. 2g).

Assuming a scenario where all farmers in the Ethiopian Rift Valley substitute tractors to their oxen, the proportion of farmers not retaining any residue in their field is predicted to decrease from 69% to 18% (Fig. 2b and d). Concomitantly, the proportion of farmers retaining at least 1 t ha\(^{-1}\) of crop residues would increase from 3% to 25%. Assuming a scenario where all the farmers in the Ethiopian Rift Valley would close the yield gap, the proportion of farmers not retaining any residue in their fields would further decrease to 13% and the proportion of farmers retaining at least 1 t ha\(^{-1}\) of crop residues would increase further to 60% (Fig. 2f). Finally, assuming a scenario where all farmers in the Ethiopian Rift Valley both substitute tractors to their oxen and close the yield gap, the proportion of farmers not retaining any residue in their fields would be 5% only, and the proportion of farmers retaining at least 1 t ha\(^{-1}\) of crop residues would be as high as 83% (Fig. 2h).
4. Discussion

4.1. Current cereal residue use

In Western Kenya, the majority of farmers retained over 80% of crop residues in their field (Fig. 2a), as there appear to be little competition with other uses such as feed or fuel (Fig. 1). This is consistent with previous studies conducted in the study area (e.g. Jaleta et al., in press). However, only about a third of the farmers retained at least 1 t ha$^{-1}$ of crop residue. Other farmers retained quantities of crop residues that may be too low to have a significant impact on soil organic carbon and other soil parameters.

In the Ethiopian Rift Valley, the bulk of the cereal residues produced is fed to livestock: over 80% of all the teff, wheat and barley straw, and about two thirds of the maize and sorghum stover (Fig. 1). About 20% of maize and sorghum stover was also used as fuel. As a result, the majority of farmers in the Ethiopian Rift Valley did not retain any crop residue in their fields (69%, Fig. 2b). Only 3% of the farmers in this site retained at least 1 t ha$^{-1}$ of crop residue. Previous studies have also found that the bulk of the crop residues produced in the Ethiopian Rift Valley is too fed to livestock (e.g. Wondatir, 2010).

The lower use of crop residue for feed in Western Kenya compared with the Ethiopian Rift Valley may be the result of a lower cattle density (Table 5). It can also be attributed to a more intensive livestock production system--as illustrated by the higher proportion of cows in the herd, the higher milk production, and the lower heifer/cow ratio. Indeed, reliance on crop residue tends to diminish when livestock production intensifies, as more energy-dense rations become necessary (see Section 4.3.1 below).

The adoption of CA sensu stricto in the Ethiopian Rift Valley (i.e. including crop residue mulching) is thus not possible without increasing the quantity of crop residues retained in the field. Although the bulk of crop residues is retained in the field in Western Kenya, for the majority of farmers, this translate to quantities per surface area that may be too small to yield any benefit, and may even be detrimental if retained as surface mulch (Baudron et al., 2012). In both sites, expanding the niche where CA fits--and more generally feeding both the livestock and the soil--requires to increase the quantity of crop residues retained as mulch. This can be achieved (1) by improving the quantity and quality of the available crop residues, and (2) by reducing crop residue demand for livestock feeding. These alternatives are explored in the next sections.

4.2. Closing the yield gap to increase maize stover yields

Maize yield in both sites is limited by N and P, as the attainable yield increase with increasing application rates in these nutrients (Fig. 3). However, the efficiency with which N and P are used is low, as the large majority of farmers (78% in Western Kenya and 68% in the Ethiopian Rift Valley) do not produce half of the yield they are expected to achieve given the quantity of N and P applied (Fig. 4). This may be the results of a high incidence of yield-reducing factors such as weeds, pests and diseases, and/or of poor response to N and P.

Simple management options such as increasing crop density (Olsen et al., 2005) or combining low doses of pre-emergence herbicide with manual weeding (Versteeg and Maldonado, 1978) may control weeds effectively. CA may also lead to a reduction in weed pressure over time, as reduced soil disturbance generally lead to a reduction in seed banks, rhizomes and tubers in the soil (Swanton and Weise, 1991). Cover crops, often used in CA systems, may also control weeds through shading and/or allelopathic effects (Teasdale, 1996). Pests can be repelled from the crop by exploiting semiochemicals produced by particular plants (e.g. ‘push-pull’ system controlling stem borer in Kenya, Hassanali et al., 2008). Finally, the incidence of diseases can be reduced by the use of genetically-resistant varieties (e.g. maize lines resistant to Streak virus, Rodier et al., 1995).

Crop response to a given nutrient is in part regulated by the availability of other limiting resources (Janssen et al., 1990) and the fulfillment of other plant requirements in terms of e.g. aeration and physical support (Vanlauwe et al., 2010). Water is probably a limiting factor in both sites as demonstrated by the positive response of maize yield to increasing rates of surface mulch (Fig. 6). In most cases, surface mulching increases water storage in the soil thanks to reduced water runoff and soil evaporation (Findeling et al., 2003; Scopel et al., 2004). The use of cover crops or trees may lead to similar benefits (Burgess et al., 1998; Ong et al., 2000).

If all farmers in both sites were to close the maize yield gap--by increasing the quantity of nutrients applied, using site-specific technologies to control yield reducing factors, and ensuring maximum nutrient use efficiency, the majority would be able to retain 1 t ha$^{-1}$ of crop residues or more (Fig. 2e and f). From the large basket of technologies available to achieve this goal, adoption will be the result of complex interactions between the technology itself and the farming context including e.g. labour demand vs. labour availability, cost vs. financial capital, information about the technology, knowledge and skills required, input and output market,
and policies. Meanwhile, if these technologies can increase the quantity of crop residues produced, their adoption will only lead to increased quantities of residues retained in farmers’ fields where they are accompanied with interventions aiming at reducing crop residue demand for livestock feeding. This is explored in the following section.

4.3. Reducing crop residue demand for livestock feeding

4.3.1. Providing incentives to increase livestock productivity

The profitability of milk production tended to increase with decreasing amounts of maize residues in the ration (Fig. 7a). This is probably due to the high price of maize residue relative to its low nutrient density and its high fiber content. Indeed, for a given milk price, the profitability of dairy production is a function of the feeding costs, the genetic potential of cows (in terms of milk yield), and the extent to which cows fulfill their genetic potential with the available feed. The latter depends on the daily energy intake, which is determined by feed intake, feed energy concentration and digestibility. As the digestion and transit of fiber is slow compared to e.g. starch, feed intake decreases due to ruminal fill with increasing total fiber content (measured by the NDF). Feed intake of cows appears to be maximal with NDF between 25 and 30% (VandeHaar and St-Pierre, 2006). In comparison, the mean NDF value of maize stover in Ethiopia is 77.9 ± 3.1% (http://192.156.137.110/feeddB/FeedDB.html). This analysis suggests that dairy producers would respond to increased market demand (stimulating the goal of profit maximization through dairy) by shifting from feed rations composed mainly of cereal residues to feed rations with lower fiber content and higher energy density. This agrees with the model proposed by Romney et al. (2004), who state that the quantity of crop residues fed to livestock as a function of the degree of intensification can be described by an inverted U-shaped curve. As livestock production systems intensify, crop residues are first substituted to grazing, and planted fodders and supplements are later substituted to crop residues.

Milk production cost per litre also tended to decrease with increasing milk yield (Fig. 7b). This is due to the fact that fixed costs (i.e. energy required to maintain the cow’s normal metabolism – e.g. breathing, maintaining body temperature) decrease relative to total costs (i.e. energy for maintenance and production) when individual productivity increases (VandeHaar, 1998). A typical cow producing 15 kg of milk per day exports half of the energy it ingests (the other half being used for maintenance), whereas a cow producing 45 kg of milk per day exports three quarters of the energy it ingests (VandeHaar and St-Pierre, 2006). As a result, dairy farmers generally intensify by selecting for animals with increasingly high genetic milk yield potential. For example, when shifting from milk production for self-consumption to milk production for the market, dairy producers of the Kenyan highlands tend to shift from East African Zebu breeds to high-yielding breeds such as Friesian and Ayrshire (Bebe et al., 2003). As genetic selection increases energy requirement but does not increase the ruminal capacity of improved animals (Coppock, 1985), they require rations that are increasingly energy-dense i.e. containing no or little cereal residue.

Therefore, livestock producers of the developing world are likely to respond to increasing market demand for livestock products by using rations that are poor in cereal residues but rich in energy-dense ingredients, and by selecting for cows with high individual productivity and requiring energy-dense rations to fulfill their genetic potential. If all farmers in Western Kenya were to intensify dairy production to a level where cows would be fed on rations containing no maize residues, the proportion of farmers unable to retain any crop residue in their fields would halve (Fig. 2c) at high intensification level, farmers may feed their dairy cows with high-value forage produced on-farm or purchased, agro-industrial by-products such as cakes from oil crops, and from grain in situation where this is profitable (i.e. value-addition) and does not threatens food security (Lenné and Thomas, 2005). However, livestock intensification may also result in a reduction of the resilience of smallholder systems, due to increased reliance on external inputs and a possible shift from many animals with low productivity to fewer animals with higher productivity (Moll et al., 2007). Moreover, the reliable supply of improved animal genetics and of veterinary products and services, however, is a major barrier to livestock intensification in most of sub-Saharan Africa (McDermott et al., 2010).

4.3.2. Providing substitutes to the current functions of livestock

In Western Kenya, milk production is an important function played by livestock, as demonstrated by the facts that the cattle herd was dominated by cows, and that milk productivity per cow was almost three times higher than in the Ethiopian Rift Valley (Table 5). Manure production is another important function played by livestock in this site, as demonstrated by an average collection intensity of manure eight times higher than in the Ethiopian Rift Valley, and by an average application rate of manure four times higher. The importance of these two functions is further illustrated by the fact that the number of dairy cows and the quantity of manure used in the farm have a significant influence on crop production in Western Kenya (Fig. 5a).

Intensification of dairy production in Western Kenya - to a level where cows would be fed on rations containing no maize residue—would lead to half of the farmers to be able to retain at least 1 t ha⁻¹ crop residues in their field (Fig. 2c). Such intensification may lead to a reduction in livestock number, which may ultimately threatens manure production, the second important function of livestock in this site. However, manure use efficiency could be improved by simple technics such as flooring and roofing of the stall (Rufino et al., 2006).

In the Ethiopian Rift Valley, animal traction is an important function played by livestock, as demonstrated by the fact that the cattle herd was dominated by oxen (Table 5). Moreover, the number of pairs of oxen owned by a farm had a significant influence on the crop production of the farm (Fig. 5b). Therefore, we hypothesized that the adoption of cheap and low powered tractors—e.g. two-wheel tractors—to replace oxen would significantly increase the quantity of crop residues retained in the field. From a sustainability point of view, mechanization is dependent on fossil reserves deposits whilst draught animals are sustained by short-term nutrient deposits—i.e. biomass (Schiere et al., 2002). However, the opportunity cost of labour, land and capital for keeping draught animals the whole year while they may only be put to productive work few days per year should also be considered (Ehui and Polson, 1993). More than half of the farmers would retain 1 t ha⁻¹ crop residues or more in their fields if tractors were substituted to oxen in the Ethiopian Rift Valley (Fig. 2d).

4.4. How much surface mulch is required?

Through a combination of interventions, almost all farmers would be able to retain at least 1 t ha⁻¹ cereal residues in their fields (Fig. 2g and h). The quantity of biomass available for mulching being acknowledged as a major limitation to CA in Africa, this would expand the niche where CA fit. However, farmers are only likely to retain this biomass as surface mulch and not plough it in if the practice leads to a short-term increase in maize grain yield. In the following section, we question what quantity of mulch is optimal to increase maize grain yield in the two study sites.
In Western Kenya, surface mulching had no effect on maize grain yield during the short rains (Fig. 6a), while quantities of maize stover applied as surface mulch in excess of 1 t ha⁻¹ did not improve maize grain yield during the long rains (Fig. 6b). Similarly in Melkassa, quantities of maize stover applied as surface mulch in excess of 3 t ha⁻¹ did not improve maize grain yield (Fig. 6c). This suggests that (1) soil mulching does not always improve maize grain yield, and (2) when soil mulching is beneficial, maize grain yield does not increase linearly with the quantity of surface mulch applied. These results agree with the ones of Larbis et al. (2002) who found that increased residue retention resulted in increased crop yield up to a retention rate of 50%, but that further mulch retention did not improve crop yield significantly. Therefore, the target of 30% soil cover often used in CA (Erenstein, 2003) may not lead to the most profitable crop residue allocation. This target originated from the US Corn Belt Region, a region that cannot be compared with sub-Saharan Africa (Blanco-Canqui and Lal, 2009). Therefore, there is a need to understand the site-specific crop response to mulching, from which appropriate recommendations can be formulated.

Under certain circumstances, mulching may lead to yield penalty. Cereal residues have a wide C:N ratio and their decomposition may lead to temporary N immobilization (Palin et al., 2001; Zbiliske et al., 2002). In high rainfall areas, mulching may exacerbate water-logging (Rusinamhodzi et al., 2011). Conversely, in areas receiving frequent and small amounts of rainfall, mulching may reduce water infiltration as rainwater is intercepted by the mulch, temporarily stored, and subsequently lost to evaporation (Cook et al., 2006; Kozak et al., 2007). In areas characterized by periods of prolonged drying (e.g. where a distinct rainy season is followed by a distinct dry season) a surface mulch may facilitate water flow from the soil to the atmosphere through capillarity, by maintaining the topsoil wetter for a longer period of time, and increasing the evaporation rate compared with a bare soil (Unger and Vigil, 1998).

In areas where mulching leads to yield penalty and/or where the quantities of crop residues available for mulching are too small (due e.g. to low crop productivity), minimum-tilage with no mulch may still improve water balance and short-term crop productivity if surface rugosity is purposefully increased. In the semi-arid area of Ethiopia, strip tillage was found to result in significantly higher maize yield and lower surface runoff compared with conventional tillage systems (Temesgen et al., 2012). For hand-hoe based systems, planting basins have been shown to increase soil moisture content compared to conventional ploughing in Zimbabwe and Zambia (Mupangwa et al., 2008). In addition to these tillage practices, a variety of structures – such as contour bunds, grass strips, pits, furrows, dikes, and terraces – may contribute to soil and water conservation at plot- and landscape-level in the absence of surface mulch (Vohland and Barry, 2009).

Thus, the availability of crop residues for soil mulching may not be as limiting for the wide adoption of CA in Africa as suggested in previous analyses (e.g. Giller et al., 2009, 2011; Andersson and Giller, 2012). Indeed, crop yield does not appear to increase linearly with increasing quantities of surface mulch in many situations, implying that crop residues could be shared between soil mulching and livestock feeding without negative consequence for crop productivity. Under other circumstances, mulching may not be desirable and thus competition for residue between CA and livestock may not exist. Last but not least, ‘CA without mulch’ may yield a number of benefits for smallholders, including cost- and or labour-savings during land preparation. If implemented in combination with other soil and water conservation measures, it can gradually raise biomass production up to a level where ‘full CA’ (i.e. including all three principles) can be implemented (Tittonell et al., 2012).

5. Conclusions

Through this study, we suggest that a large basket of technologies is available to allow Eastern African farmers to retain substantial quantities of cereal residues in their fields without threatening their livestock production. Residue retention is not only a prerequisite to CA but it is also the most viable option. African smallholders have to maintain their fields in a productive state. As the need for agricultural intensification in Africa becomes more pressing, fueled by increased demand for agricultural products, ‘feeding’ both the soil and the livestock becomes a necessity. We argue that the focus on trade-offs and competition for scarce crop residues diverts research efforts away from proposing alternatives: the question should not be ‘if’, but ‘how’ crop residues can fulfill the need of both the soil and the livestock. In each site, the adoption of the technologies that best fit local circumstances may be stimulated by putting in place the right incentives.

Although this paper argues that the retention of crop residues is possible in mixed crop-livestock systems of Eastern Africa, this would not be achieved by any single technology. Modifying the supply-side of crop residues without altering the demand-side is unlikely to increase the quantity of crop residues retained in the fields, particularly in areas where farmers tend to maximize the number of livestock they keep. The promotion of combinations of technologies, rather than single component technologies, would be needed, though this requires a major shift in the way research and development is being conducted.

Finally, competition for cereal residues between livestock feeding and soil mulching may not be as limiting for the adoption of CA as previously stated. Indeed, the impact of surface mulching on crop productivity is equivocal, and is not reflected in the blanket recommendation of a 30% soil cover. Thus, there is a need to understand the site-specific crop response to mulching, from which recommendations can be formulated. There should be situations where mulching does not improve crop productivity, or even has a detrimental effect on crop yield. Mulching should not be an end by itself, and the focus should be on processes (e.g. increased water-use efficiency), not on technologies.

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